Note 17

Exhaust Valve Problems and their solutions

Early Engines

When Maybach in 1885 designed a 264cc water-cooled 1-cylinder engine for Daimler, he placed the exhaust valve at the side of the cylinder as the obvious way to operate it directly from a camshaft alongside the crankcase, itself driven easily from the adjacent crankshaft. It was probably about 24mm head diameter (EVD). The maximum stress in a 4-stroke poppet exhaust valve – in the stem – need not be high (depending on the (Head/Stem)^2 ratio) and it is compressive while under cam control at opening and closing, being tensile while the spring is controlling the valve in between. The stress range is repeated at RPM/2 so that material fatigue life at high temperature – up to 800C without internal cooling – is important, as is creep life and resistance to attack by combustion products. The material available in 1885 was only steel and probably a mild carbon type was used (say 0.2% C) as would have been used in boiler-tubes exposed to firebox gases. The side-valve had the advantage that a lost valve head would not necessarily wreck the engine (and this was a favourable design point considered in production engines and some racing units for a further 4 decades).

Nickel Steels

Shortly after the early Daimler engines appeared, Riley in 1889 (618) published the work on Ni/Fe/C alloys which opened the way to greater life, or greater stress for the same life, at high temperatures. Advantage was taken of this, inter alia, for the manufacture of gun barrels (a gun being a piston engine which ejects its piston after the power stroke!). Krupp of Germany in particular exploited this use (and also employed it for battleship's armour plate). It is not known specifically what use was made of these Ni/Fe/C alloys for exhaust valves at the time, but in 1916 Ricardo specified a 3% Ni type for his 1st tank engine – one of the few parts for which he was not restricted by low supply priority to low-grade steels (242).

Wright Aero-Engines

When the ingenious Wright brothers built their own 3.3L 4-cylinder aero-engine in 1903, not having found a proprietary unit of sufficient Power/Weight ratio, they used originally cast-iron heads with steel stems screwed–in (their exhaust valves moved vertically below a horizontal combustion chamber which was only slipstream-cooled). Many valve failures were experienced (the location here also must have alleviated the resultant damage) and, despite several engine developments, continued over the next 10 years (592,616).

Stainless Steel

In 1912/1913, while experimenting with Cr/Fe/C alloys for gun barrels, Brearley (head of the Brown-Firth collaborative laboratory) discovered accidentally the stainless (i.e. oxidation-resisting) properties of a 12.8%Cr/86.96%Fe/0.24%C mix (hereafter figures only; refs 618,629,669). This then offered superior resistance to scaling at exhaust temperatures.

Valve Size Advantage

Meanwhile in engine high-power design the breathing and valve-bounce-speed advantages of 4 overhead valves per cylinder (4v/c) had become clear and this also assisted the life of exhaust valves. This is because, with a fairly-constant thickness of valve-head to minimise mass and so maximise valve-bounce RPM, the smaller the diameter the better the ratio of rim flow area through which much of the heat escapes during the valve-shut period (2/3rds of the time with early engine timing) to the head area by which the heat enters the valve (see Sub-Note A). Whereas a typical 1908 12L 4-cyl. engine with 2 v/c would have had an EVD around 100mm, the 1912 7.6L 4-cyl. Peugeot with 4 v/c was down to 54mm and the 1914 4.5L 4-cyl. Mercedes, also 4 v/c, to 43mm. Although Fiat led a return to 2 v/c in 1921, their "GP Car-of-the-Year" in 1922, being only 2L and 6-cyl., had EVD = 40mm so was not breaking new ground there.

WW1 Advances

It is interesting, in looking at this valve size aspect, that, when Henry Royce designed his 1st aero-engine of 20.3L in 1914 and retained the 4.5 inch (114.3mm) bore he knew so well from the 1907-onwards 40/50 HP ("Ghost") production car, his new overhead-valve design (based on the 1912 DF80 Daimler 7.3L 6-cyl. aero-engine which had run in a car in the 1913 Sarthe GP, an example having been obtained by R-R, (305)) required an EVD of only 54.8mm. This engine (later named "Eagle"), though containing 50% more parts than any other in British WW1 service, was "undoubtedly" the most reliable so that an overhaul life still only about 100 hours was nevertheless nearly x2 that of the next-best (242). Ref (616), referring to WW1 aero engines in general, states that "exhaust valve failures were probably the most prevalent cause of ….short engine life". The exhaust valve material of the Eagle is not known but (669) states that high-Cr steels were used in WW1 for aero-engine exhaust valves – a "Firth Aeroplane Steel" (FAS) was available in 1914 with 13Cr/86.6Fe/0.4C.

Ref. (616) reports , without mentioning applications, that during WW1 alloys up to 25Ni/Fe/C were tried to combat exhaust gas attack but were found to have poor creep resistance.

The late-WW1 US "Liberty" 27L V12 engine, 2 v/c, used "High Speed Steel" (HSS) valve material derived from the early 1900s cutting-tool alloy of 19W/4Cr/Fe/C developed by Taylor and Wright in America (618). While this had the necessary strength at high temperatures, it had poor corrosion resistance (616)(of course, in cutting-tool use the material would have been cooled externally with soapy-water). The Liberty valves were 69.9mm EVD and the head was very thin (399). The engine had a short overhaul life when it eventually entered service.

"Tungsten Steel" – which must mean HSS – actually had been used previously by Pomeroy (Senior) for the 1914 GP Vauxhall exhaust valves (224). It was also used by Halford and Pullinger for the exhaust valves of the 1916 BHP aero-engine, redesigned from the original Porsche-designed pre-WW1 Austro-Daimler unit built under licence by Beardmore. The BHP also took advantage of size effect by changing a single 71mm valve to dual (602).

Ref. (669) also reports that Krupp, just before WW1, had introduced V2A containing 20Cr/7Ni/72.8Fe/0.2C. It is likely that this was used in German engines. The Cr + Ni content made this an "Austenitic" steel, so-called because the grain structure at operating temperatures was similar to a well-known Fe/C metallurgical phase named after Robert-Austen, a late-19th C researcher (618).

Austenitic Steels

Post-WW1 the Versailles Peace Treaty forbade the manufacture of German high-power aero-engines. Perhaps because of this in 1923 Krupp sold rights to their patented austenitic steel to Firth and Brown, possibly on the initiative of Brearley. These firms developed their own versions (669). In particular Hatfield, Brearley's successor at the collaborative laboratory, produced the now-famous 18Cr/8Ni/73.8Fe/0.2C stainless-steel, sold by Firth's as "Staybrite".

The problem of the exhaust valve was brought under control a little later by a revised formulation which balanced Cr and Ni and added some W and other elements. The originator is not given in (669) but an early example was Kayser-Ellison KE965 with 13Cr/13Ni/2.5W/1.3Si/0.7Mn/69.1Fe/0.4C (with the usual important maximum controls on impurities such as S and P and the appropriate heat treatment). This alloy was specified, more or less, by Air Ministry DTD49b and also by En54 (639).

This proprietary alloy KE965 was the exhaust valve material of 1st choice in British high-power designs for the next 3 decades. Craig (no doubt referring to British makes) asserted that austenitic material was used initially in air-cooled racing motor-cycle engines and then was taken up for aero-engines (12).

Internal Cooling

At about the same date that the new austenitic exhaust valve alloy was available, a further step in valve design had been taken at Daimler which became nearly-standard practice when engines were Pressure-Charged (PC). This company had experimented with PC during WW1 to restore power at altitude and had settled on mechanical supercharging (MSC) with the Roots blower (637,468). Post-War they applied MSC as a short-term power-boost system to various 4-cyl. touring and racing cars. When Porsche joined them in 1923 he improved the existing M7294 IL4 2L MSC engine by, amongst other things, fitting exhaust valves whose larger-diameter stems were drilled and then plugged after partial filling with a quantity of Hg. When the valve reciprocated this filling was shaken up-and-down the stem and so conducted heat more rapidly from the solid head to further up the stem from whence it could escape via the guides to the cooling water (468). This revised engine won the 431 km 1924 Targa Florio. Porsche in the meantime had designed a completely-new unit with continually-engaged higher-boost supercharger, the 1924 M218 IL8 2L Grand Prix engine in which the stems of all-4 v/c were filled partially with Na salts (468). This filling liquefied at operating temperature and wetted the metal surfaces, unlike Hg, and so conducted heat away more effectively.

The exacerbation of the exhaust valve problem by PC was solved not only by improved austenitic steel and internal cooling, as described above, but also by the near-simultaneous adoption of alcohol-base fuels, i.e. fuels whose latent heat of evaporation was a multiple of that of petrol, some of which entered the cylinder neat and reduced metal temperatures (see Appendix 2).

In aero-engine research of the mid-20s, using petrol fuel and with many firms building air-cooled types, i.e., with hotter cylinder heads than water-cooled designs, it was Heron (an Englishman, ex Royal Aircraft Factory in WW1) with the US Army Air Corps who followed Midgely in developing internal Na-cooling of exhaust valves (616). These valves were then produced in quantity by the Williams Rich Corporation (708). At a critical moment in the British preparations for the 1931 Schneider Trophy air race, a sample American Na-cooled valve was brought to England by Banks and given to Rolls-Royce to copy under sub-licence from the Bristol Aeroplane Co., who had a licence from the Rich Corpn. (ST competitors had to use nationally-made parts)(619). When fitted into the R-type engine and run with the 20% petrol/70%benzole/10%methanol fuel at the mixture strength necessary for the Supermarine S6B seaplane to perform competitively within the rules, Lovesey, the development engineer, was able to see in the open exhaust ports that the "Bright Cherry Red" of the uncooled 50.8mm parts (about 850C, which would pre-ignite the charge) was changed to "almost black" when the internally-cooled valves were fitted – probably 300C cooler (615,689).

This type of valve, in KE965 alloy (also used for solid inlet valves*) was later included in the Rolls-Royce "Merlin" and "Griffon" aero-engines, produced in vast numbers during WW2 (632).

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*Surplus Merlin inlets were turned-down post-WW2 by motor-cycle racing men to serve as exhaust valves, e.g., in Excelsior "Manxman" 250cc!

Sodium-cooled exhaust valves – or, in the case of the Mercedes-Benz 1934-1939 M25 to M165 engine series, Na-, and then a reversion to Hg-cooling in hollow-stem Krupp WF100 valves (15Cr/14Ni/2W/2Si/0.8Mn/65.75Fe/0.45C, very like KE965)(30) – were virtually standard for supercharging to the end of the 1st GP PC era in 1951. However, it is noteworthy that MG in 1936 were able to run *solid* KE965 valves (810) of only 28.6mm EVD at an absolute pressure at the inlet valve (IVP) up to 3 Atmospheres (ATA) in record tune on high-alcohol mixture, once the valve guides had been lengthened in an ad hoc way to improve heat escape (139,394). This shows the inverse size advantage when combined with the parts-cooling effect of alcohol.

Fuel Cooling

During the latter part of the 1st PC era – all engines mechanically supercharged – Grand Prix HP/Litre was raised by taking advantage of this ability with alcohol fuel to run super-rich (i.e., compared with the stoichiometric ratio) so that, as well as cooling the charge in the inlet manifold by evaporation, some fuel passed as liquid into the cylinder and there cooled by final evaporation the valves and piston. The cost of this on consumption has been estimated as follows:-

Data Sources:- 31,607,684

Year	1937	1938	1951
Car	Mercedes W125	Mercedes W154	Alfa 159M
HP/L	97	158	270
Relative Specific Power	Datum	1.63	2.78
Fuel, %age Alcohol	65 [10 Ethanol] [55 Methanol	86 Methanol	99 Methanol
Relative Consumption Per HP.Hour	Datum	1.65	2.44

Internal Cooling in NA engines

Sodium stem-cooling was used for the exhaust valves of some British air-cooled racing motor-cycles in the last few seasons before WW2 (675). The temperature drop here would not have been necessary to prolong life but would have enabled compression-ratio to be raised. Post-War the same principle was extended sometimes to inlet valves, egs, air-cooled Nortons, Mercedes M196, BRM P56 and Porsche 908 & 912 air-cooled sports-racing engines, where the cooling would also improve breathing. In the M196 of 1954-1955, the directly-injected moderate-alcohol fuel was sprayed partially onto the exhaust-valve head and so cooled it additionally.

In the air-cooled Nortons of 1953-1954 exhaust heat was taken from the valve guide by an oil gallery and then dispersed in a separate oil/air cooler.

WW2 Advances

During WW2 the need for high-temperature creep-resisting materials for jet engine turbine blades led in the UK to the development by the Wiggin company of the Nimonic alloys, which started from the pre-War Nichrome formula (80Ni/20Cr) made for electric-fire elements, i.e., a material which resisted oxidation at bright cherry red temperature but, of course with no stress. By adding small amounts of Ti, Al, Fe and C and heat-treating the creep resistance at useable stress was increased (618). From the early-50s this 1941 turbine-grade Nimonic 80A (75Ni/20Cr/2.4Ti/1.2Al/0.5Fe/0.04C (685)) was used for NA solid exhaust valves. Coventry Climax (amongst others) had them in their FPF engines of 1957-1961, which powered the World Champion Cooper cars in 1959-1960 (34). However, Hassan (Climax Chief Engineer) reported that quite bad seat scuffing and ridging occurred so that tune was lost.

Post-WW2 Advances

Because of the drawbacks mentioned to Nimonic 80A, in the 1961-1966 series of Climax FWMV V8 1.5L engines Hassan adopted for their solid exhaust valves a new austenitic alloy 21-4NS (21Cr/4Ni/9Mn/0.25Si/0.4N/64.85Fe/0.5C, (644)). This work-hardened because of the N content and gave “almost complete” absence of valve failure (34). Its Ultimate Tensile Strength at 800C was 20 tons/sq.in. (309 MPa) compared to 16 (247 MPa) for KE965 and its resistance to scaling was x4 (885). It was much cheaper than N80A.This 21-4NS alloy with an addition of 0.2% Columbium was also used for the famous Ford Cosworth FVA and DFV engines over 1966-1983 (583).

Turbo-Charged Engines

Reversion to PC by Turbo-Charging (TC) over 1977-1988, using inter-coolers to prevent knocking on the regulation petrol fuel, but without the advantage of alcohol fuel to cool the cylinder parts as described above in the 1st PC era, needed a return to Na-cooled valves. The head itself, as well as the stem, probably would have been hollow. The frequent highly-spectacular blow-ups of such engines, always ascribed by commentators to the turbocharger, while no doubt often correct, would in many cases be provoked by a broken valve head entering the turbine.

Titanium Exhaust Valves

In 1989 the regulations once again banned PC. Power increases then demanded higher RPM, calling for higher Bore/Stroke ratio, only possible if higher valve speeds could be accepted. To the latter end lower-density Ti-alloy valves were adopted not only for inlet valves but also, astonishingly, for exhausts. Honda had found it possible to do this in 1983 in their V4 750cc 4 v/c racing motor-cycles, where EVD was only 25mm (97). The alloy used was Ti6Al4V (317),i.e., 6Al/4V/90Ti, a “work-horse” specification commercially-available after having been developed at great expense for the US Air Force for medium-temperature gas turbine applications in the ‘50s. In motorsport it had been first used to reduce the mass of inlet valves around 2 inches diameter by American tuners of their large V8 push-rod engines in the ‘60s. These valves were made by the US specialist company Del West. The density ratio (Ti6Al4V)/(KE965) = (4.4g/cc)/(8.1g/cc) = 0.54, so that the maximum advantage on Mean Valve Speed would be $1/\sqrt{(0.54)} = 1.36$ (reduced in practice by non-Ti parts in the valve-gear).

The advantage of Ti-alloy for *all* valves had not reached Grand Prix engines before TC, with its higher heat-flow, made it impossible*, but post-TC nearly all makers adopted it. Exhaust valves in the V10 3.5L, then 3L, units which mostly dominated the post-1988 scene began at about 30mm diameter, but they have risen steadily as B/S ratio has been increased further via the adoption of Pneumatic Valve Return Systems (“Air Valves”), being around 33mm in 1998. Del West were still the major supplier (317).

The thermal conductivity of the Ti-alloy is only about half that of austenitic steel (623), which makes its successful use for exhausts somewhat surprising but, of course, their life now has only to be about 2 1/2 hours to cover race-day “warm-up” plus the race before they are discarded at overhaul.

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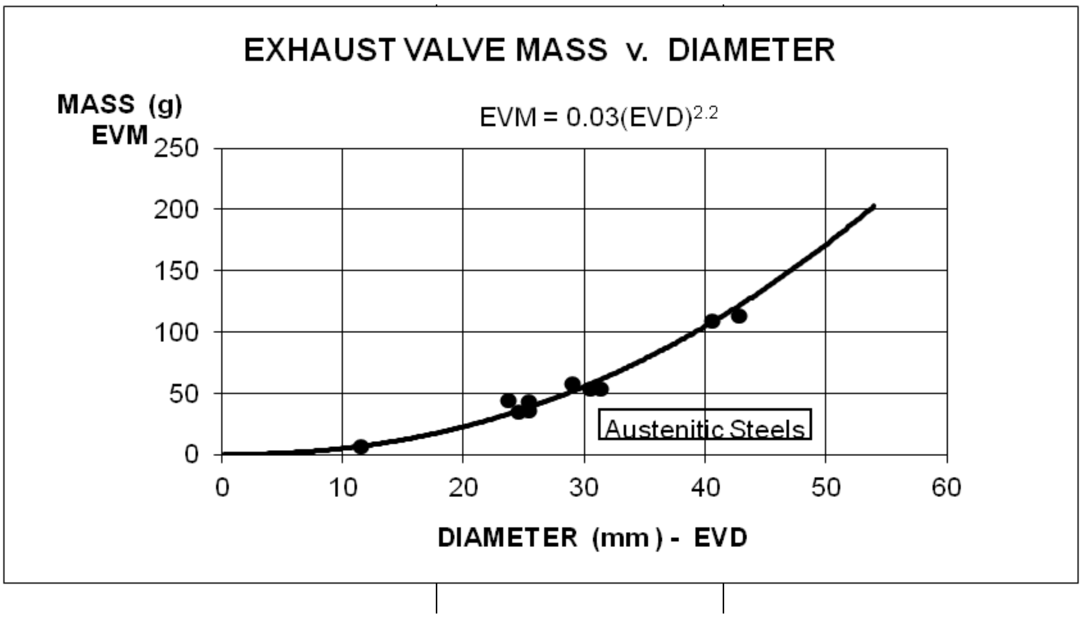
*Porsche actually developed for the TC version of the Type 912 air-cooled sports-racing engine a Ti-alloy Na-cooled *inlet valve (*302). This engine powered the winner of the 1972 CanAm Championship. Apart from retaining the cooling advantages of the previous Na-cooled steel valve, mentioned previously, this might have permitted a more-rapid-opening cam, as well as giving an engine weight reduction.

Sub-Note A
Solid Exhaust Valve
Data

ENGINE	DASO	EVD mm	EVM g
COSWORTH FVA	583	29	58
CLIMAX FWA2	132	30.5	53.1
CLIMAX FPF 1.5	131B	40.6	108.9
CLIMAX FPF 2.5	131B	42.8	112.5
CLIMAX FWM	33	*24.6*	34.6
CLIMAX FWMA	33	*25.4*	35.4
CLIMAX FWMV1	34	*31.4*	53.2
CLIMAX FWMV6	34	*23.7*	44.3
CLIMAX FWMW	34	*25.4*	42.5
HONDA RC149	14	11.5	6

Italics = Approx.



Since the chart shows that EVM is proportional to (EVD)^2.2 and not (EVD)^3, it follows that valve dimensions normal to the head were not *pro rata* to the diameter in the design convention used over this range of 1954-1966 engines. Therefore the (Rim-section Area)/(Head Area) ratio declined with increasing diameter and, other things being equal, the larger the valve the hotter it would run.

One of the (many) advantages of the 4 v/c Ford Cosworth FVA over the 2 v/c Climax FPF, both 4 cyl. of about the same capacity (1.6L v. 1.5L), was that EVD = 29mm compared with 40.6mm (and later 42.8mm).

In "Motor Sport" Jan. 1970 (853), referring to the Ford Cosworth BDA IL4 1.6L (developed from the FVA for Ford road-going high-performance models) it says:-

> "*…the smaller valves show less tendency to burn out than the large single valve fitted….*
> *..to a normal Lotus-Ford…*"

The Lotus-Ford was also DOHC IL4 1.6L and the EVD difference was:-

L-F = 36.8mm;   BDA = 25.4mm; i.e. 31% smaller.